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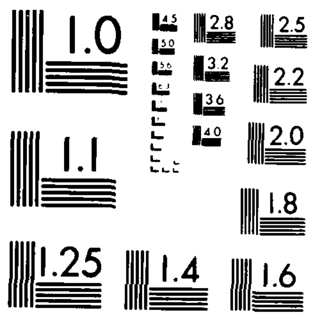

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1. REPORT NUMBER AFOSR-TR- 83-0142	2. GOVT ACCESSION NO. AD-A126409	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) "Binary Color Vision for Industrial Automation."		5. TYPE OF REPORT & PERIOD COVERED Final 4/1/82 12/31/82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dr. David Milgram Dr. Michael Chen		8. CONTRACT OR GRANT NUMBER(s) F49620-82-C-0069
9. PERFORMING ORGANIZATION NAME AND ADDRESS Machine Intelligence Corporation 330 Potrero Avenue Sunnyvale, Ca. 94086		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2305/K1 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS Director of Electronic & Material Sciences Air Force Office of Scientific Research Building 410, Bolling AFB DC Attn: Dr. J.A. Neff		12. REPORT DATE February 28, 1983
		13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

DTIC ELECTE APR 5 1983 S D A

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

Same as #16

18. SUPPLEMENTARY NOTES

The paper "Binary Color Vision" based on this research was presented at the 2nd International Conference on Robot Vision and Sensory Control, Stuttgart, Germany November, 1982.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Industrial automation, computer vision, binary images, color filters.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This project addresses the questions of the near-term utilization of color by existing state-of-the-art binary vision systems. Using the experimental testbed, it was demonstrated that under suitable thresholding and filtering, the spectral contents of color scenes could be artificially controlled. Rejection of unwanted colors or background clutter could be performed. Under single threshold selection, discriminations of objects identical in shapes and sizes but different in colors could be achieved by utilizing the

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luminance effect of colors. Color encoding combines the description of colors and thresholding and provides a simple interface to computer processing.

The introduction of color discriminations for current machine vision processing can significantly extend their range of applications. Experiments using color filters to separate the natural image into color component images show that binary image processing is a valuable next step in color region recognition.

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AFOSR-TR- 83-0142

FINAL REPORT

AFOSR CONTRACT NUMBER F49620-82-C-0069

BINARY COLOR VISION FOR INDUSTRIAL AUTOMATION

MACHINE INTELLIGENCE CORPORATION

330 Potrero Avenue

Sunnyvale, CA, 94086

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TABLE OF CONTENTS

[I] ABSTRACT

This project addresses the questions of the near-term utilization of color by existing state-of-the-art binary vision systems. Using the experimental testbed, it was demonstrated that under suitable thresholding and filtering, the spectral contents of color scenes could be artificially controlled. Rejection of unwanted colors or background clutter could be performed. Under single threshold selection, discriminations of objects identical in shapes and sizes but different in colors could be achieved by utilizing the luminance effect of colors. Color encoding combines the description of colors and thresholding and provides a simple interface to computer processing.

The introduction of color discriminations for current machine vision processing can significantly extend their range of applications. Experiments using color filters to separate the natural image into color component images show that binary image processing is a valuable next step in color region recognition.

[II] TECHNICAL DISCUSSION

[II-A] INTRODUCTION

Color-perception is an important human ability and it exerts profound influences on industry, business, science, engineering, as well as art and design. It is also one of the strongest visual cues (others are edges, grey-scale, depth and shades, etc.) that we use to distinguish far/near objects, and probably the only cue to distinguish colored objects with same shape, size, and features. Color-perception can be considered a very individual experience. It is affected by the physical characteristics of the source and the transmitting medium, by the physiology of the retina and the visual nervous system, and also by the psychological state of processes of the cerebral cortex in interpreting the signals sent through the retinocortical pathway. The retinex (retina-and-cortex) theory [8] of human color vision basically treats a color as a three-part report from the retina, independent of the flux of radiant energy. The human eye has evolved to see the world in unchanging colors, regardless of shifting, unpredictable and uneven illumination. This "insensitivity" to changing lighting makes color vision attractive for industrial applications.

Color vision is particularly useful in industrial automation to recognize, search, sort, and manipulate colored parts or color-coded objects. The use of color permits part discrimination where grey-scale information alone is insufficient and often times avoids the complicated and time-consuming grey-scale analysis by using thresholding. The purpose of this research is to demonstrate that color, together with position, size, and shape informations can be extracted from a scene viewed through a TV camera. Commercial (black and white) binary vision systems have begun to substantially affect productivity in automated manufacturing. Their value results from their programmed ability to locate, measure, and identify significant visual characteristics of manufactured objects or processes. At present, these systems work on data which have been binarized through the careful control of threshold and lighting in order to provide high-contrast images. This has given rise to an image processing technology based on the extraction of silhouettes of workpieces. Such silhouettes are sufficient to accomplish inspection, recognition, and mensuration and to determine part position and orientation.

The study of machine binary color vision must deal with acquisition of colors, differentiation of colors, filtering and selective processing of colors, measurements of colors (colorimetry), and together with all the features (such as size, shape, and position etc.) that a binary vision system can extract from a scene.

Research in the digital processing of color images is sparse. Remote sensing has concerned itself with the estimation of pixel statistics using multispectral satellite data. For a review of this literature, see [12]. There has been recent interest in color among computer vision researchers[7],[10],[13]. Deserving particular mention is the work of Ohta et. al.[14]. Using registered red, green and blue images, they found that linear combination of these images were easier to segment than the pure color intensity images. Several studies[17][18] of machine color vision for industrial applications have been reported. One example was the research done by Ito (1975)[5],[11]. He utilized color information in an inspection system for IC mask patterns. Patterns of IC masks were illuminated by red, green, and blue light, respectively. Defects of these mask patterns could be identified by the optical compositions of the patterns under illumination of the primary color light sources. Loughlin (1982)[9] reported Inspectrum - a full color inspection system which checks the shape of an industrial part and provides detailed qualitative inspection of surface color. Basically, this system permits part discrimination through decoding the PAL video signal, digitizing the separated R, G, and B components and storing the data in buffer memory for later comparison. Position information can be obtained through the "inspection points" under joystick software control. One disadvantage of this approach is that position information is not acquired automatically but requires human interaction. Fiorini (1982) [2] reported a color sensing system which functions as an intelligent peripheral unit with a supervisory computer which can program up to 256 saturation levels for each chromatic components: red, green, and blue. This peripheral unit sends back three bits, one for each component, flagging overflow or underflow of programmed saturation levels by the chromatic contents of the sensed object. This system does not provides the size, shape, and position information about the inspected parts. It is capable of sensing moving objects and is insensitive to lighting change in the environment.

[II-B] RESEARCH OBJECTIVES

The investigation of binary machine color vision was divided into different phases to attain the following objectives:
(1) assembly of a color-imaging environment using MI VS100 as the major component.
(2) demonstration of color-encoding scheme for binary patterns.
(3) methods for recombinations of binarized color images.
(4) demonstrations of use of color and shape for object recognition.

The following subtasks were selected to achieve the above goals:

* definition and selection of color filters covering the visible spectrum.

* characterization of transmittance curves for color additive filters, color subtractive filters, and color temperature compensation filters by using instruments such as monochromators.

* characterization of spectral distribution curves of existing light sources including tungsten halogen lamps, fluorescent tubes, ultra-violet and short-wave tubes, and infra-red long wave lamps.

* assembly of light source, color filter sets and wheel holder, and MI VS-100 experimental test-bed.

* investigation of proper lighting for color machine vision, control of reflected light and emitted light, and selection of opaque, transparent, glossy and matte objects for study.

* experiments with monochromatic objects and singling out variables which affect recognition.

* tricolor coding technique for color objects.

* use of tricolor coding for color objects recognition covering visible spectrum.

* logical combination of multiple narrow-band images for specific discrimination tasks.

[II-C] BACKGROUND OF BINARY AND COLOR VISION

VS-100 System

The VS-100 vision system (See Figure 1.) is a commercial binary vision system. It receives a video grey-scale image from a solid-state or vidicon camera and thresholds it into a binary(black/white) image that is run-length encoded for data compression and subsequent processing. Computer algorithms perform a connectivity analysis of the encoded images, building data structures that represent essential features of each contiguous region. The vision system characterizes blobs on the basis of distinguishing features such as area, perimeter, minimum and maximum radii, and number of holes (See Figure 3.). The system can be trained to analyze new objects simply by showing them to the system. Object recognition is performed using a nearest-neighborhood classifier operating on a user-selectable set of the features. Interaction with the system are menu-driven, using light-pen or keyboard input. Menus (See Figure 2.) allow various system choices such as selection of the threshold value, window size, operating options and parameters for specific applications. Calibration, training-by-showing, storing and loading of prototype data can all be accomplished readily.

The Imaging Sensor - Camera

The cameras that were used to perform the experiments were GE TN2200 and TN2500[3] solid state camera with CID(Charge Injection Device) imaging array sensor. For the latter, the CID sensor contains over 60000 light sensing picture elements(pixels) in a 3x4 aspect ratio format. The typical spectral responsivity function of CID sensor in shown in Figure 5.2.

Threshold and Histogram

Binarization has been a central topic of interest to computer vision and numerous approaches have been published[15][16]. Generally in binary vision system, a histogram is a graph that measures the number of pixels occurring at grid points along a grey scale. In order to obtain a stable image on the monitor, it is necessary to set the threshold number at a point on the histogram that will slice the grey scale and redefine the pixels to be either black or white. The histogram is a guide for accomplishing this. The ideal shape of the histogram, including a properly adjusted camera and high contrast scene, will have two well defined peaks. One peak on the histogram corresponds to the pixels in the background, the other peak to pixels in the object. Setting the threshold at the valley that occurs between the two peaks ensures that the correct pixels will become either part of the background or part of the image. The image will then be a

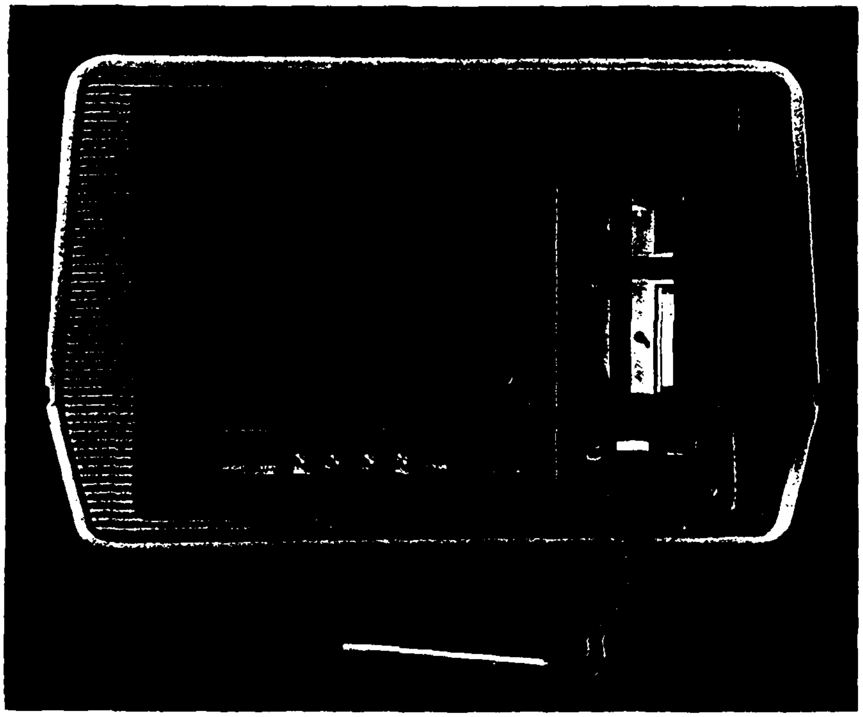


Figure 1. The MI VS-100 binary vision system.

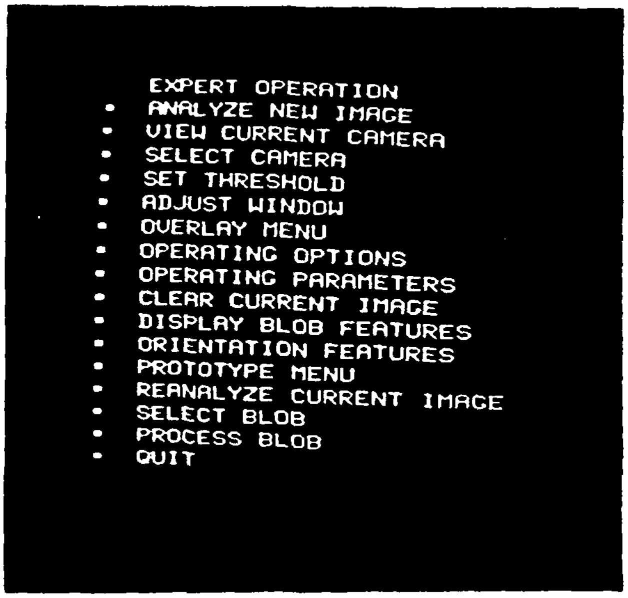


Figure 2. A typical menu of the VS-100 system.

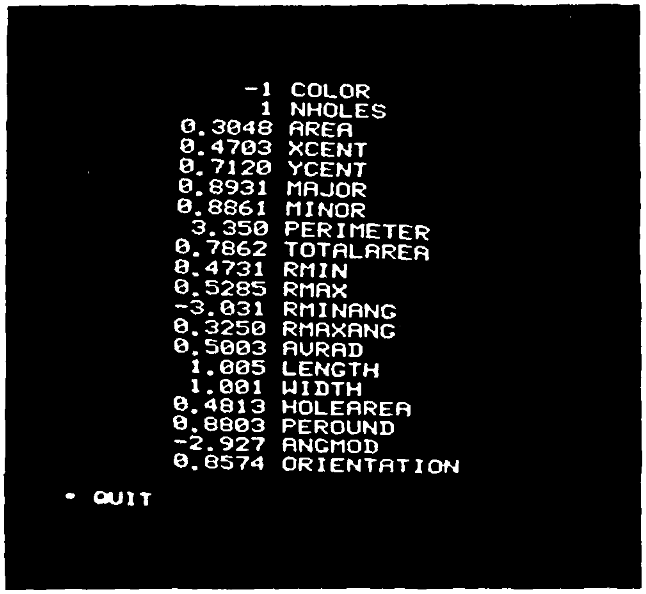


Figure 3. Display of features and their values.

stable, high contrast silhouette of the object being viewed.

The HISTOGRAM command in the VS-100 causes the system to sweep through the threshold range from 255 to 0, displaying the thresholded image at each setting and graphically indicating the number of pixels changing from black to white at each threshold value. High values on the histogram corresponds to threshold settings where the image changes rapidly. Low values correspond to threshold settings where the image is stable. For most objects the optimal setting of the threshold is in the stable area corresponding to the low point between the two peaks.

Color Image

A wide range of colors can be reproduced, to the sat 'action of the eye, by the addition of only three monochroma : light sources, e.g., red, green, and blue. The three CIE 'andard primaries are monochromatic light of wavelength 700 r (red), 546.1 nm (green), and 435.8 nm (blue).

A digital image is defined by a function of 2-D posi , say I(m,n), defined at chosen grid points of the image. For a achromatic grey-scale image, the function I is scalar-valued, its value being the brightness of the image at a certain point. For color images, three values must be specified at each point, i.e. the function I is vector-valued and has three components. A common choice of the three components is that of the so-called red, green and blue (R, G and B) components. The R, G, and B components can be transformed to other quantities, more closely associated with our visual senses of color, such as luminance, hue, and saturation.

A simple and commonly used transformation is defined here for reference.

$$RC = R / (R+G+B)$$

$$GC = G / (R+G+B)$$

$$Y = aR + bG + cB$$

where a, b, and c are suitably chosen scaling constants. Y gives the luminance of the image pixel and RC and GC provide the chromaticity information. Hue and satuaration can be deduced by converting RC and GC to a polar coordinate system (Nevatia, 1976)[10]. It is important to notice that the luminance is expressed as the linear summation of the contributions from the R, G, and B components. This formula will be expressed in a more explicit form in the later sections.

Luminance

Luminance indicates the amount of light intensity, which is perceived by the eye as brightness. In a black-and-white picture, the lighter parts have more luminance than the dark areas. Different colors have different shades of luminance, however, as some colors appear brighter than others. The luminance really indicates how the color will look in a black-and-white reproduction.

The eye does not respond equally to radiated energy of all visible wavelengths. There is wide variation between observers, and the response is also a function of light intensity. Based on thousands of measurements on human observers, the average eye is considered to respond according to the luminosity function of the standard observer. A standard luminosity function has a Gaussian-like bell-shape distribution (relative luminosity versus wavelength) which centers at 546 nm.

The luminance of a surface is the effect on the average sensor(eye) of the light emitted by a unit area of the surface. It is the integrated effect of the sensor(eye) response y(l) and the visible light power radiated by the surface E(l), both of which are functions of the wavelength l. The integration is expressed by

$$\text{Luminance} = \int 680\ E(l)y(l)dl \text{ lm/unit area}$$

where lm is the abbreviation for lumen and the radiated power E(l) is in watts per unit area. The constant 680 lm/W is the luminosity of radiant power at the peak of the luminosity curve, at 546 nm.

The brightness of a surface is defined in terms of a surface which reflects the light in perfectly diffuse fashion. Such a surface has a brightness of 1 foot-lambert (fl) for each lumen incident upon it if it does not absorb any energy, i.e., has reflectivity of unity.

The typical CID (charge injection devices) spectral responsivity curve of the GE solid state cameras is shown in Figure 5. The curve indicates that CID also has the greatest responsivity to green color(around 560 nm). The responsivity curve extends far beyond 700 nm which indicates that CID has a broader responsive range than humans in the infrared regions.

Hue, Saturation and Chrominance

The hue describes the intrinsic nature of the color, i.e., red, green, cyan, purple, etc. The color itself is its hue or tint. A red apple has a red hue; green leaves have a green hue. The color of any object is determined primarily by its hue. Different hues result from different wavelengths of the light producing the visual sensation in the eye.

Saturation is a measure of color intensity, i.e. its pastel versus vivid quality. Desaturated colors are whitish or washed out. Saturated colors are vivid, intense, deep, and strong. Pale or weak colors have little saturation. The saturation indicates how little the colors is diluted by white. It is important to note that a fully saturated color has no white. Then the color has only its own hue, without any other components that could be added by the red, blue, and green of white.

The term chrominance is used to indicate the combined effect of hue and saturation of a color. In color TV, the 3.58-MHz modulated subcarrier' color signal more specifically is the chrominance signal. The chrominance includes all the color information, without the brightness. The chrominance and the brightness together specify the picture color information completely. Chrominance is also called "chroma".

The Luminance Effect of Colors

It is intuitively more understandable to discuss the luminance effect of various colors by studying the primaries used in TV color signals. The transformations[4][7] to obtain the X, Y, and Z primaries for color vision, based on the FCC primaries, are

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.608 & 0.174 & 0.200 \\ 0.299 & 0.587 & 0.114 \\ 0.000 & 0.066 & 1.112 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

These X, Y, Z primaries, are nonphysical and do not represent real colors. They can represent real electric signals but must be electrically transformed (using an electrical analog of the transformation equations) to R, G, and B signals before being displayed. The Y signal is the luminance signal. It is representative of the black-and-white TV signal that would be derived from the same matter by a high-performance monochrome camera. The X and Z signals carry the color information system, i.e., the nonluminance content. The Y (luminance signal) contains the brightness variations of the picture information. This signal is formed by adding the primary red, green, and blue video signals in the proportions (rounding off the third digit below the decimal point to simplify calculations) :

$$Y = 0.30R + 0.59G + 0.11B$$

These percentages correspond to the relative brightness of the three primary colors. Therefore, a scene reproduced in black and white by the Y signal looks the same as when it is televised in monochrome. The Y signal has its maximum relative amplitude of unity, 1.0 or 100 percent for white, because it includes R, G, and B. This value for white is calculated as

$$Y = 0.30 + 0.59 + 0.11 = 1.00$$

As another example, the cyan color includes G and B but not R. Then the Y value for the cyan is calculated as

$$Y = 0 + 0.59 + 0.11 = 0.70$$

All the voltage value of the Y signal can be calculated in this way. The resulting voltages are the relative luminance values for each of the following saturated color. If the Y signal alone were used to reproduce the pattern, it would appear as monochrome bars shading off from white at the left to grey in the center and black in the right.

white	yellow	cyan	green	magenta	red	blue	black
1.00	0.89	0.70	0.59	0.41	0.30	0.11	0.00
111	110	010	101	100	100	001	000

The second line indicates the binary coding for the eight colors above (color encoding technique will be explained in more detailed in a later section). All the colors are assumed to be saturated vivid colors. In natural scenes, however, most colors are not 100 percent saturated. Then any color diluted by white light has all three primaries. Assume 70% saturation for yellow. Now this color has two components: 70% saturated yellow and 30% white.

70% Yellow produces	0.70R	0.70G	0.00B
30% White produces	0.30R	0.30G	0.30B
Total output is	1.00R	1.00G	0.30B

$$Y(\text{luminance}) = 0.30(1.00) + 0.59(1.00) + 0.11(0.30) = 0.923$$

We can see that this color is "brighter" than the saturated yellow which has a luminance value of 0.89. Note that the addition of white to desaturate a color increases the luminance value and decreases the chrominance value, compared with 100% saturation.

[II-D] RESEARCH RESULTS

ANALYTICAL AND EXPERIMENTAL METHOD

The first step in the study of color machine vision is to extract the color information from a scene. Natural scenes in general consist of more than one color. Human beings use color information as a powerful clue in object recognition. Traditional binary machine vision has neglected the color component in the scene by thresholding the grey-scale image. This is an original study in extracting color information from a scene through filtering, yet still preserving the processing speed and other advantages of a "binary" vision system.

The study of colors involves usage of narrow- or broad-band filters installed in front of viewing TV cameras or broad-band light sources, or by directing manipulating the chrominance (and luminance) signals in a color TV camera. The choice of narrow or wide band filters depends on several factors. The number of colors to be discriminated, the distribution of these colors in the visible spectrum, and the amount of processing time involved determine how many filters to use and what bandwidths to use.

The commonly used color filters are color additive filters and color subtractive filters. Color additive filters are broad bandpass and edge interference filters which transmit one of the three primary colors (red, green and blue). Combined in suitable mixtures, these colors can produce most of the color sensations which human vision is capable of perceiving. The color subtractive filters are designed for use at 45 degrees and reflect the primary colors red, green, and blue. The transmitted colors are the complementary colors of the primaries. These are cyan (minus red), magenta (minus green), and yellow (minus blue). Minus colors are often used electronically and photographically to reproduce the primary colors. For example, the strength of the red signal at a vidicon may be determined by obtaining the white light signal and subtracting from it the minus red (cyan) signal. In fact, a minus red channel, a minus blue channel, and a white light channel are sufficient to obtain the information to reproduce the primary colors, and is the basis of some inexpensive color television cameras.

Narrow-band color filters are chosen to select the bandpass of the field of view. Only light with the specified narrow bandwidth can be transmitted and thresholded. The advantage of this approach is that color can be more accurately acquired and differentiated. The shortcoming is that in order to extract a large number of colors, a corresponding large number of narrow-band filters has to be utilized.

Discrete objects with distinct single color regions can be differentiated by utilizing the selective filtering property of filters. Objects with several color patches can be analyzed in the following way. The individual patches are analyzed and features computed. The identified individual patches can later be "recombined" through utilization of features such as area, center of blob, pixel counts. The underlying reason for this is that these particular features for the whole object are the linear summation of the same features of the constituent color patches, assuming that these multicolored objects are isolated in the field of views (no overlapping or stacking of objects).

Selecting and Characterizing the Light Source

Color sensing results from the compound spectral effect of the color filters, the light source, and the imaging sensors. Manufacturers of filters usually provide the transmittance curves for precision filters. The spectral responsivity functions of the sensors and the spectral power characteristics of the light sources are also important parameters which must be measured or obtained from the suppliers of the instruments.

The human eyes in general do not discriminate composite colors very well. A source may appear white but has a far-from-flat spectrum. In order to select the appropriate light source, the authors have performed a detailed monochromator test of all existing light sources available in the laboratory. These sources include tungsten halogen lamps, fluorescent lamps, infrared and ultraviolet sources. The spectral characteristics of these sources are documented by obtaining the spectrographs for all sources. This procedure is important in selecting a light source which has relatively flat bandpass in the visible spectrum.

Decision was made to use the "north sky-light" fluorescent lamp as the light source to perform the experiment to be discussed. We chose fluorescent lamp for high luminance and most importantly, for more uniform spectral power distribution than other sources such as tungsten ones(See Figure 5.1.).

Characterizing the Color Filters

A similar experiment was performed to characterize the transmitting characteristics of the color filter sets. The filters tested included a set of color additive filters, a set of color subtractive filters, and a set of color-temperature compensation filters manufactured by Melles Griot Corporation. The first set consists of red, green and blue filters. In addition to the transmittance curves supplied by Melles Griot, the spectral property of these filters was actually tested by using a monochromator. The transmittance curves of these filters under illumination of the fluorescent lamp are shown in Figure 4.2 - 4.4. These curves clearly show how the filters cut off certain ranges of wave-lengths in the spectrum.

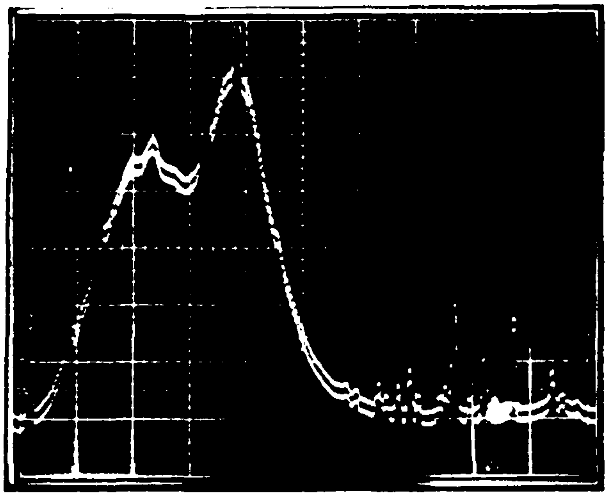


Figure 4.1. The spectral distribution curve of the fluorescent lamp used to perform the experiments described in this paper.

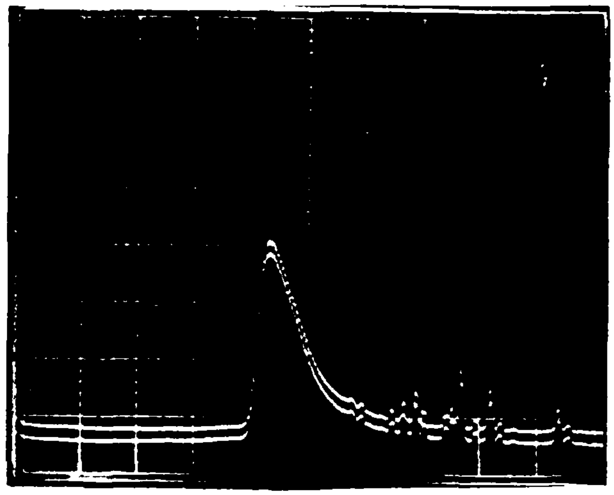


Figure 4.2. The transmittance curve for the red filter with the fluorescent lamp as the light source.

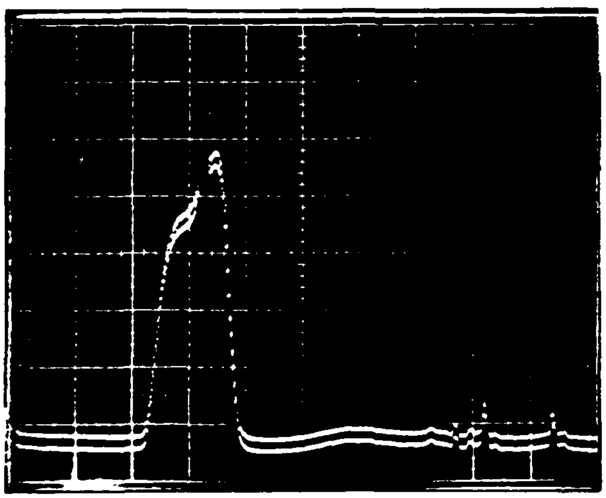


Figure 4.3. The transmittance curve for the green filter with the fluorescent lamp as the light source.

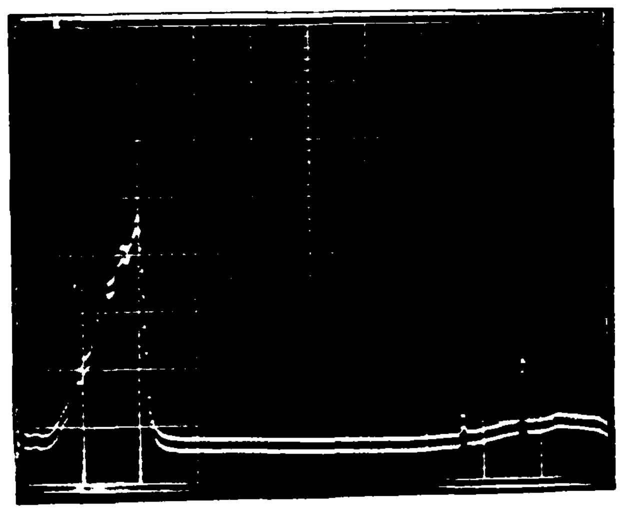


Figure 4.4. The transmittance curve for the blue filter with the fluorescent lamp as the light source.

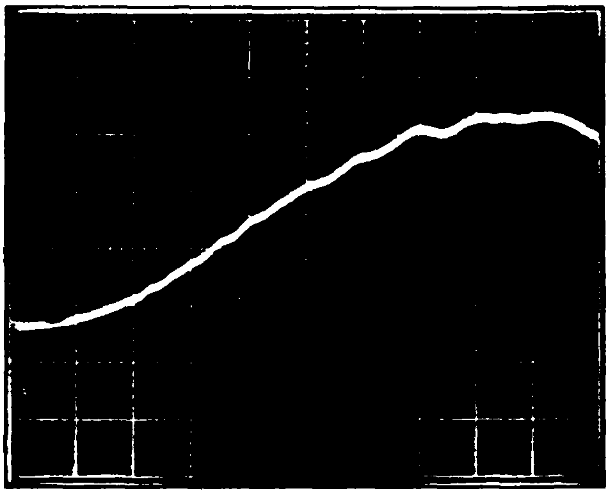


Figure 5.1. The spectral distribution curve of a tungsten lamp.

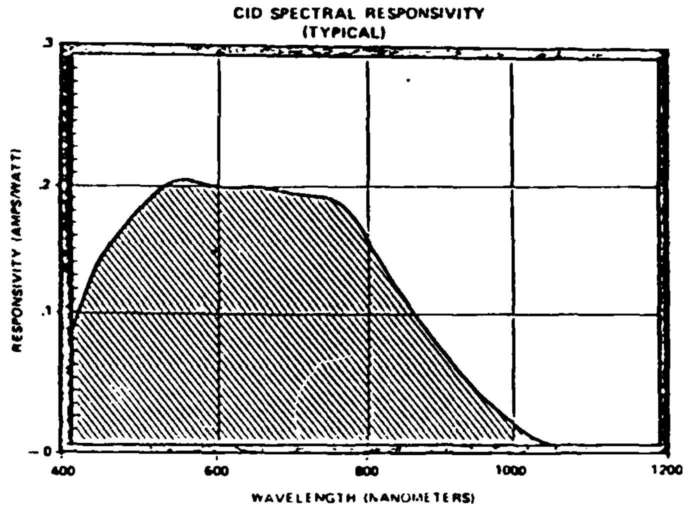


Figure 5.2. The typical spectral responsivity curve of the CID solid-state camera used in the experiments.

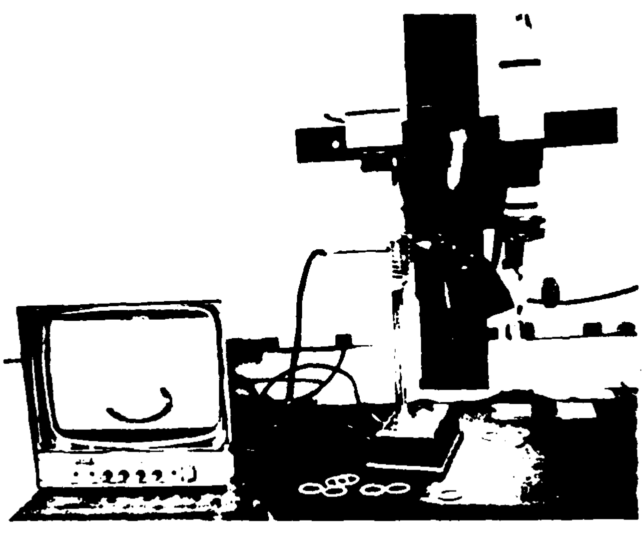


Figure 6. The experimental setup for color discrimination using binary processing.

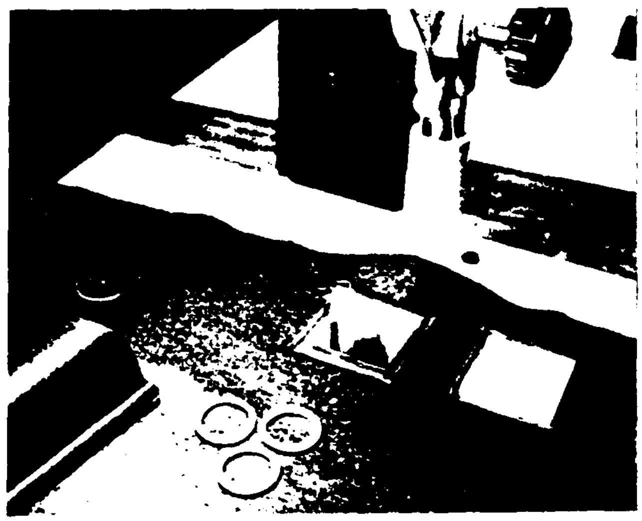


Figure 7. Close-up view of the color rings used in the experiments and the filters.

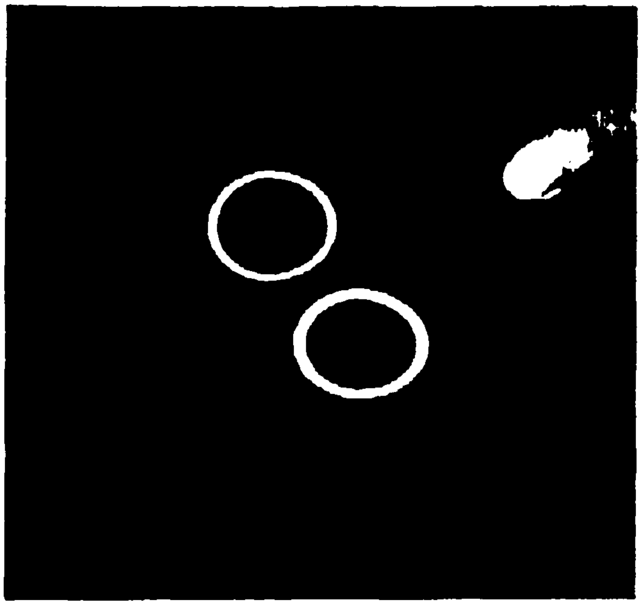


Figure 8.1. The raw video image of the red, green and blue rings with the finger pointing at the blue ring.

Figure 8.2. At a threshold value of 96, the green ring appears first because of its highest luminance.

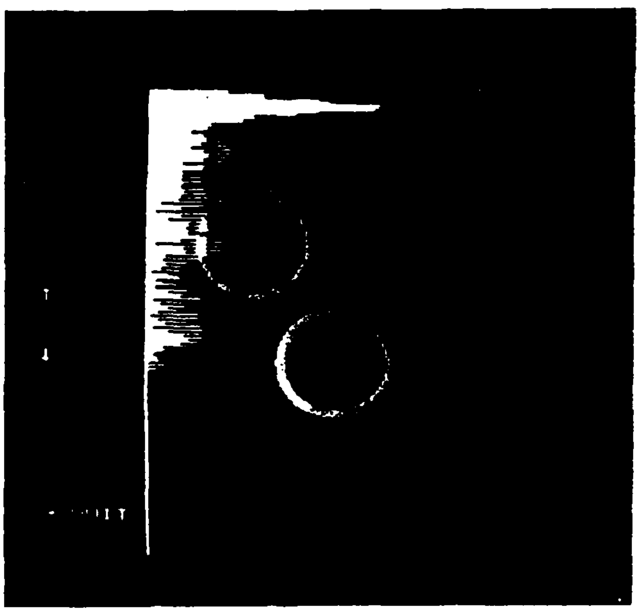


Figure 8.3. At a threshold value of 49, both the green and red ring show their thresholded images.

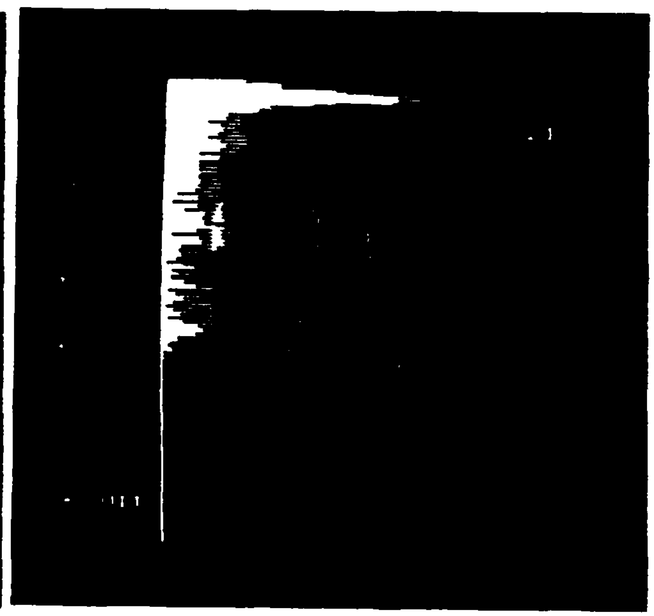
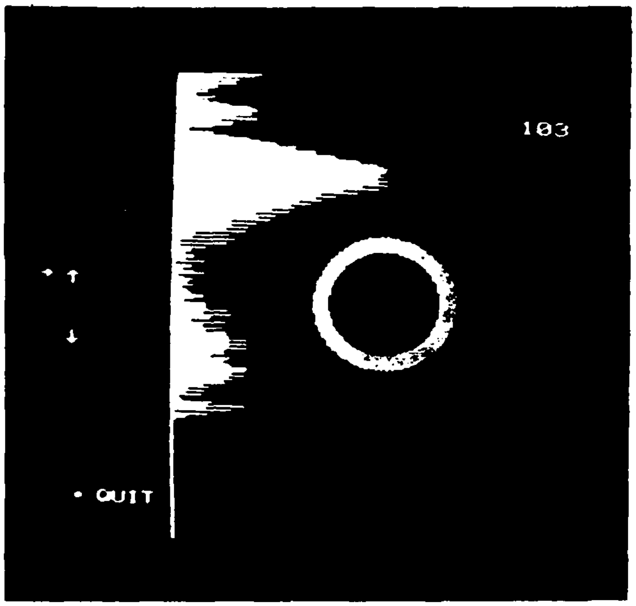


Figure 8.4. At a threshold value of 21, all three rings appear on the monitor. The blue ring seems to be thinner than the other two ring.



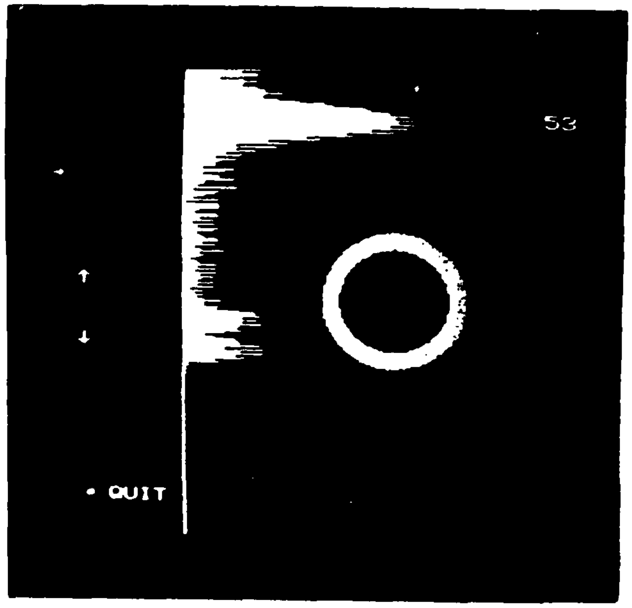


Figure 9.1. The histogram of the red ring without red filter.

Figure 9.2. The histogram of the red ring with red filter.

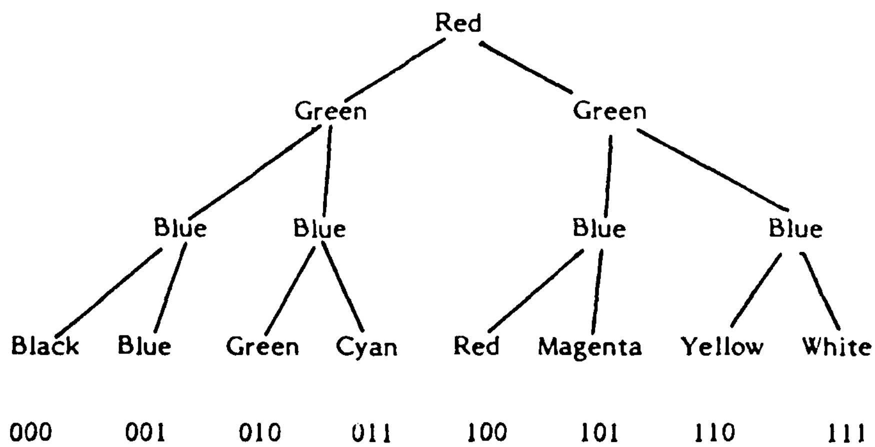


Figure 10. The classification and coding technique used in analyzing colors. A 3-bit code is associated with each classified color. A maximum of eight colors can be classified using this method.

Rejection of Unwanted Colored Object using Color Filters

The methods of discriminating colors using current machine vision system fall into two categories: methods based on selection of spectral bandpass and methods based on luminance effects of color objects.

The are two problems involved in the latter process. The first concerns the optimal selection of single threshold for all colors. The second is the confusion caused by the fact that different colors may have the same luminance value. This makes any discrimination based on luminance alone unreliable unless during the training period the ambiguous situations are avoided.

An optimal solution to this is through the usage of a combination of the above two methods. Confusion caused by nonunique mapping between the color space and the luminance space can be minimized by using filters to eliminate undesired spectral contents. If a small number of filters is used(say, R, G, and B filters) to discriminate colors widely-spaced in the visible spectrum, then the filters alone will be sufficient to distinguish them using "binary" color vision. For colors with overlapped spectral contents, the luminance effect of colors will be useful in color-differentiation in combination with filters in "binary" vision system.

Luminance Effect of Colored Objects

An experimental testbed (See Figure 6., 7.) was established to experiment and evaluate machine color vision. This test-bed consisted of a MI VS-100 binary computer vision system, a color filter holder with adjustable supporting stand, the color-additive filter set, a set of plastic color rings with identical shape and size as test objects, and the optional MI DS-100 Machine Vision Development System (Chen and Milgram, 1982)[1] for developing special software for color-coding and performing the training and recognition functions. An experiment was performed to assess the feasibility of discriminating multiple colors using single filter. A set of color rings were prepared as the testing objects. The set of rings used consists of red, pink, yellow, and blue. Placed under a TV camera connected to the MI VS-100 vision system, the blue ring was invisible (rejected) to the system under a red filter (In an automated factory, this feature allows automatic rejection of unwanted color objects in the background. This also saves computing time by neglecting the otherwise complicating objects in connectivity analysis). A comparison of the filtered and unfiltered view would identify the blue ring.

As explained in the previous sections, luminance indicates the amount of light intensity, which is perceived by the eye as brightness. Different colors have different shades of luminance as some colors appear brighter than the others. Relative luminosity curves have been produced by color scientists to show the hue/luminance relationship. The relationship indicates that the green hues between cyan and orange have maximum brightness. The rings showed different total pixel-counts(or area) for different colors under the same thresholding value. This is a "feature" that the VS-100 binary vision system can utilize to perform discrimination task for parts with the same feature-set except differences in colors. The authors have successfully used this property to distinguish the colors described.

Figure 8.1.-8.4. show the histograms and the thresholded images for the red, green and blue rings at three different threshold settings. It is interesting to notice that the green ring appears first as the threshold sweeps from the bottom to the top in grey levels, followed by the red ring, and then by the blue ring. It was pointed out in the previous section that green appears brightest in comparison to the other undiluted colors. This phenomenon can also be easily observed in the raw video image that shows the three rings with a black background. The finger points at the blue ring which appears darkest.

Color-Coding Technique

Utilizing color filters for the three primary colors, color-encoding can be performed. Basically, this operation is, in principle, similar to the early design of color video cameras which used a rotating color-filter wheel triggered by the vertical sync signal for color separation.

We can use a 3-bit color-encoding technique to code and distinguish eight colors. Figure 10. shows the binary tree classification method used in color encoding and classification. We can see that 3-bit encoding works best for three primary and their complementary saturated colors. For desaturated colors, because of the dilution by white(in other words, mixture with equal amount of red, green, and blue primaries), ambiguity will arise. For example, light green, pink, and light blue may all be indistinguishable from white in coding since they are all coded 111. Another example is that yellow and orange may both have the same coding 110, i.e., both of them will pass the red and green filter test and fail the blue filter one, despite that they are different colors as perceived by the human eyes.

[II-E] CONCLUSION

Since color-sensing results from the compound spectral effect of the light source, the transmitting medium and intervening filters, and the imaging sensors, it is crucial to define their spectral characteristics before any analytical or experimental work be done. This effort was described in the previous sections. The importance of this is exemplified by the following example. Two colors might look identical under tungsten illumination(2860 K), but completely different in daylight(6500 K) [19].

Using the experimental testbed, it was demonstrated that: (1) Under suitable thresholding and filtering, the "spectral content" of the color scenes can be artificially controlled. (2) Unwanted color objects can be easily rejected. (3) Under single threshold selection, discrimination of objects identical in shapes and sizes but different in colors can be performed using features such as area, pixel counts, perimeter, etc. This is due to the luminance effect of different colors which manifest themselves in thresholded views as size shrinkage or expansion. (4) Using R-G-B filtering, 3-bit color-encoding can be performed for 8 colors. If we assign two bits for each color and expand from 3-bit to 6-bit, 64 colors can be encoded.

The unique aspect of this research is that color is acquired together with all other features in a "binary" machine vision system. Traditional color discrimination devices such as monochromators or spectrophotometers analyze only a beam of light instead of a scene viewed through a camera as perceived by the human eyes. By combining MI VS-100 machine vision system with color filters, color, as well as location, shape and orientation descriptors can be easily obtained. This combined color/location/orientation information can be used by a robot arm or other manipulators to distinguish among colored objects for part pickup. Additionally, through usage of filters, irrelevant colors can be rejected. This is particularly important in saving computer processing time by filtering away background clutter. Objects with connected multicolor regions can be recombined by using other features such as area, center, and pixel counts.

One form of logical image combination arises when a single object consists of adjacent regions of different colors. In this case, no single color can be expected to segment the object entirely. However, it is possible to piece together the object as the union of adjacent (or nonadjacent) regions. Generally, the shape features computed by the MI VS-100 system are such that the features for the union of non-overlapping regions can be derived from the constituent regions' features. Thus it is possible to extract multi-color object from the scene. Segmenting regions in the color domain, color codes can be identified on a complex background. In addition, the limitation posed by connectivity analysis can be removed. For example, a red object in contact with a blue one can be perceived as isolated ones through filtered views. The same scene will be easily misinterpreted by conventional binary vision system as single object because of the usage of blob processing and run-length encoding.

It is easy to imagine that the introduction of color differentiations for current machine vision processing will greatly extend the range of applications. Additional research is needed to demonstrate the advantages of coupling color filtering and binary processing so as to achieve a powerful tool for industrial computer vision applications.

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[IV] PUBLICATION LIST:

M. J. Chen and D. L. Milgram: " Binary Color Vision", Proc. 2nd International Conference on Robot Vision and Sensory Control, Stuttgart, Germany, 1982.

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[VI] INTERACTIONS AND COUPLING ACTIVITIES:

The paper "Binary Color Vision" (included as an Appendix) was presented at the 2nd International Conference on Robot Vision and Sensory Control, Stuttgart, Germany, Nov, 1982.

[VII] <u>INVENTIONS AND PATENTS:</u> NONE

[A] APPENDIX

"Binary Color Vision" by M. J. Chen and D. L. Milgram Submitted to 2nd International Conference on Robot Vision and Sensory Control, Stuttgart, Germany, 1982.

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BINARY COLOR VISION

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ABSTRACT

This paper addresses the questions of the near-term utilization of color by existing state-of-the-art binary vision systems. The introduction of color discriminations for current machine vision processing can significantly extend the range of applications. We describe our initial attempts at the recognition of binary regions derived from color filtered views.

INTRODUCTION

Color-perception is without doubt one of our most marvelous achievements, and it exerts profound influences on industry, business, science, engineering, as well as art and design. It is also one of the strongest visual cues (others are edges, grey-scale, depth and shades, etc.) that we use to distinguish far/near objects, and probably the only cue to distinguish colored objects with same shape, size, and features. Color-perception can be considered as a very personal experience. It is affected by the physical characteristics of the source and the transmitting medium, by the physiology of the retina and the visual nervous system, and also by the psychological state of processes of the cerebral cortex in interpreting the signals sent through the retinocortical pathway. The retinex[8] (retina-and-cortex) theory of human color vision basically treats a color as a three-part report from the retina, independent of the flux of radiant energy. The human eye has evolved to see the world in unchanging colors, regardless of always shifting, unpredictable and uneven illumination. This "insensitivity" to changing lighting makes it attractive for industrial applications.

Color vision is particularly useful in industrial automation to recognize, search, sort, and manipulate colored parts or color-coded objects. The use of color permits part discrimination where grey-scale information alone is insufficient and often times avoids the complicated and time-consuming grey-scale analysis by using thresholding. The purpose of this research is to demonstrate that color, together with position, size, and shape informations can be extracted from a scene viewed through a TV camera. Commercial (black and white) binary vision systems have begun to substantially affect productivity in manufacturing. Their value results from their programmed ability to locate, measure, and identify significant visual characteristics of manufactured objects or processes. At present, these systems work on data which have been binarized through the careful control of threshold and lighting in order to provide high-contrast images. This has given rise to an image processing technology based on the extraction of silhouettes of workpieces. Such silhouettes are sufficient to accomplish inspection, recognition, and mensuration and to determine part position and orientation.

The study of machine binary color vision must deal with acquisition of colors, differentiation of colors, filtering and selective processing of colors, measurements of colors (colorimetry), and together with all the features (such as size, shape, and position etc.) that a binary vision system can extract from a scene.

In the past, the reports of machine color vision for industrial applications have been sparse. One example was the research done by Ito[5](1975). He utilized color information in an inspection system for IC mask patterns. Patterns of IC masks were illuminated by red, green, and blue light, respectively. Defects of these mask patterns could be identified by the optical compositions of the patterns under illumination of the primary color light sources. Loughlin (1982)[8] reported Inspectrum - a full color inspection system which checks the shape of an industrial part and provides detailed qualitative inspection of surface color. Basically, this system permits part discrimination through decoding the PAL video signal, digitizing the separated R, G, and B components and storing the data in buffer memory for later comparison. Position information can be obtained through the "inspection points" under joystick software control. One disadvantage of this approach is that position information is not acquired automatically but requires human interaction. Fiorini[2] (1982) reported a color sensing system which functions as an intelligent peripheral unit with a supervisory computer which can program up to 256 saturation levels for each chromatic components: red, green, and blue. This peripheral unit sends back three bits, one for each component, flagging overflow or underflow of programmed saturation levels by the chromatic contents of the sensed object. This system does not provides the size, shape, and position information about the inspected parts. It is capable of sensing moving objects and is insensitive to lighting change in the environment.

VS-100 System

The VS-100 vision system (See Figure 1.) is a commercial binary vision system. It receives a video grey-scale image from a solid-state or vidicon camera and thresholds it into a binary(black/white) image that is run-length encoded for data compression and subsequent processing. Computer algorithms perform a connectivity analysis of the encoded images, building data structures that represent essential features of each contiguous region. The vision system characterizes blobs on the basis of distinguishing features such as area, perimeter, minimum and maximum radii, and number of holes (See Figure 3.). The system can be trained to analyze new objects simply by showing them to the system. Object recognition is performed using a nearest-neighborhood classifier operating on a user-selectable set of the features. Interaction with the system are menu-driven, using light-pen or keyboard input. Menus (See Figure 2.) allow various system choices such as selection of the threshold value, window size, operating options and parameters for specific applications. Calibration, training-by-showing, storing and loading of prototype data can all be accomplished readily.

The Imaging Sensor - Camera

The cameras that were used to perform the experiments were GE TN2200 and TN2500[3] solid state camera with CID(charge Injection Device) imaging array sensor. For the latter, the CID sensor contains over 60000 light sensing picture elements(pixels) in a 3x4 aspect ratio format. The typical spectral responsivity function of CID sensor in shown in Figure 5.2.

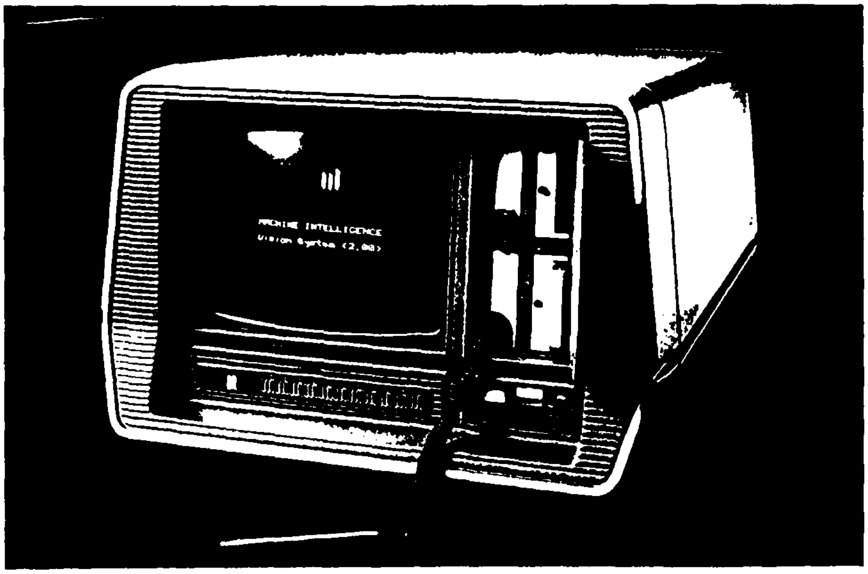

Figure 1. The MI VS-100 binary vision system.

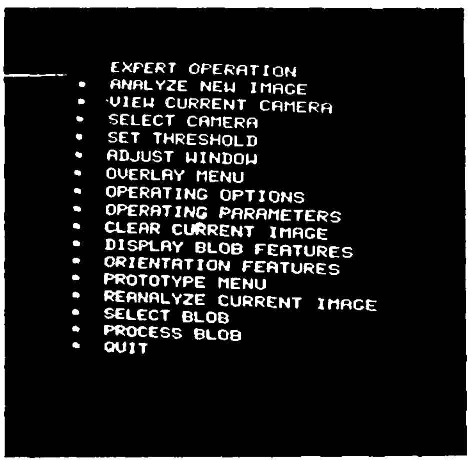

Figure 2. A typical menu of the VS-100 system.

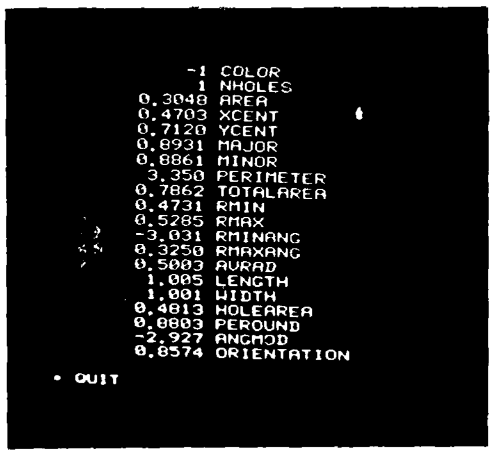

Figure 3. Display of feature names and values.

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BACKGROUND OF BINARY AND COLOR VISION

Threshold and Histogram

In binary vision system, a histogram is a graph that measures the number of pixels occurring at grid points along a grey scale. In order to obtain a stable image on the monitor, it is necessary to set the *threshold number* at a point on the histogram that will slice the grey scale and redefine the pixels to be either black or white. The histogram is a guide for accomplishing this. The ideal shape of the histogram, including a properly adjusted camera and high contrast scene, will have two well defined peaks. One peak on the histogram corresponds to the pixels in the background, the other peak to pixels in the object. Setting the horizontal arrow at the valley that occurs between the two peaks ensures that the correct pixels will become either part of the background or part of the image. The image will then be a stable, high contrast silhoulette of the object being viewed.

The HISTOGRAM command in the VS-100 causes the system to sweep through the threshold range from 255 to 0, displaying the thresholded image at each setting and graphically indicating the number of pixels changing from black to white at each threshold value. High values on the histogram corresponds to threshold settings where the image changes rapidly. Low values correspond to threshold settings where the image is stable. For most objects the optimal setting of the threshold is in the stable area corresponding to the low point between the two peaks.

Color Image

A wide range of colors can be reproduced, to the satisfaction of the eye, by the addition of only three monochromatic light sources, e.g., red, green, and blue. The three CIE standard primaries are monochromatic light of wavelength 700 nm (red), 546.1 nm (green), and 435.8 nm (blue).

A digital image is defined by a function of 2-D position, say I(m,n), defined at chosen grid points of the image. For a achromatic grey-scale image, the function I is scalar-valued, its value being the brightness of the image at a certain point. For color images, three values must be specified at each point, i.e. the function I is vector-valued and has three components.[9] A common choice of the three components is that of the so-called red, green and blue (R, G and B) components. The R, G, and B components can be transformed to other quantities, more closely associated with our visual senses of color, such as brightness, hue, and saturation.[9]

A simple and commonly used transformation is defined here for reference.

$$RC = R \; / \; (R+G+B)$$

$$GC = G \; / \; (R+G+B)$$

$$Y = aR + bG + cB$$

where a, b, and c are suitably chosen constants.[9] Y gives the luminance of the image pixel and RC and GC provide the chromaticity information. Hue and satuaration can be deducted by converting RC and GC to a polar coordinate system (Nevatia, 1976).[10] It is important to notice that the luminance is expressed as the linear summation of the contributions from the R, G, and B components. *This formula will be expressed in a more explicit form in the later sections.*

Luminance

Luminance indicates the amount of light intensity, which is perceived by the eye as brightness. In a black-and-white picture, the lighter parts have more luminance than the dark areas. Different colors have different shades of luminance, however, as some colors appear brighter than others. The luminance really indicates how the color will look in a black-and-white reproduction.

The eye does not respond equally to radiated energy of all visible wavelengths. There is wide variation between observers, and the response is also a function of light intensity. Based on thousands of measurements on human observers, the average eye is considered to respond according to the luminosity function of the standard observer. A standard luminosity function has a Gaussian-like bell-shape distribution (relative luminosity versus wavelength) which centers at 546 nm.

The luminance of a surface is the effect on the average sensor(eye) of the light emitted by a unit area of the surface. It is the integrated effect of the sensor(eye) response $y(l)$ and the visible light power radiated by the surface $E(l)$, both of which are functions of the wavelength l. The integration is expressed by

$$\text{Luminance} = \int 680\ E(l)y(l)dl \qquad \text{lm/unit area}$$

where lm is the abbreviation for lumen and the radiated power $E(l)$ is in watts per unit area. The constant 680 lm/W is the luminosity of radiant power at the peak of the luminosity curve, at 546 nm.

The brightness of a surface is defined in terms of a surface which reflects the light in perfactly diffuse fashion. Such a surface has a brightness of 1 foot-lambert (fl) for each lumen incident upon it if it does not absorb any energy, i.e., has reflectivity of unity.

The typical CID (charge injection deveices) spectral responsivity curve of the GE solid state cameras is shown in Figure 5. The curve indicates that CID also has the greatest responsivity to green color(around 560 nm). The responsivity curve extends far beyond 700 nm which indicates that CID has a broader responsive range than humans in the infrared regions.

Hue, Saturation and Chrominance

The hue describes the intrinsic nature of the color, i.e., red, green, cyan, purple, etc. The color itself is its hue or tint. A red apple has a red hue; green leaves have a green hue. The color of any object is determined primarily by its hue. Different hues result from different wavelengths of the light producing the visual sensation in the eye.

Saturation is a measure of color intensity, i.e. its pastel versus vivid quality. Desaturated colors are whitish or washout. Saturated colors are vivid, intense, deep, and strong. Pale or weak colors have little saturation. The saturation indicates how little the colors is diluted by white. It is important to note that a fully saturated color has no white. Then the color has only its own hue, without any other components that could be added by the red, blue, and green of white.

The term chrominance is used to indicate both hue and saturation of a color. In color TV, the 3.58-MHz color signal more specifically is the chrominance signal. The chrominance includes all the color information, without the brightness. The chrominance and the brightness together specify the picture color information completely. Chrominance is also called "chroma".

The Luminance Effect of Colors

It is intuitively more understandable to discuss the luminance effect of various colors by studying the primaries used in TV color signals. The transformations to obtain the X, Y, and Z primaries for color vision, based on the FCC primaries, are[47]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.608 & 0.174 & 0.200 \\ 0.299 & 0.587 & 0.114 \\ 0.000 & 0.066 & 1.112 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

These X, Y, Z primaries, are nonphysical and do not represent real colors. They can represent real electric signals but must be electrically transformed (using an electrical analog of the transformation equations) to R, G, and B signals before being displayed. The Y signal is the luminance signal. It is representative of the black-and-white TV signal that would be derived from the same matter by a high-performance monochrome camera. The X and Z signals carry the color information system, i.e., the nonluminance content. The Y (luminance signal) contains the brightness variations of the picture information. This signal is formed by adding the primary red, green, and blue video signals in the proportions (rounding off the third digit below the decimal point to simplify calculations) :

$$Y = 0.30R + 0.59G + 0.11B$$

These percentages correspond to the relative brightness of the three primary colors. Therefore, a scene reproduced in black and white by the Y signal looks the same as when it is televised in monochrome. The Y signal has its maximum relative amplitude of unity, 1.0 or 100 percent for white, because it includes R, G, and B. This value for white is calculated as

$$Y = 0.30 + 0.59 + 0.11 = 1.00$$

As another example, the cyan color includes G and B but not R. Then the Y value for the cyan is calculated as

$$Y = 0 + 0.59 + 0.11 = 0.70$$

All the voltage value of the Y signal can be calculated in this way. The resulting voltages are the relative luminance values for each of the following saturated color. If the Y signal alone were used to reproduce the pattern, it would appear as monochrome bars shading off from white at the left to grey in the center and black in the right.

white	yellow	cyan	green	magenta	red	blue	black
1.00	0.89	0.70	0.59	0.41	0.30	0.11	0.00
111	110	010	101	100	100	001	000

The second line indicates the binary coding for the eight colors above (color encoding technique will be explained in more detailed in a later section). All the colors are assumed to be saturated vivid colors. In natural scenes, however, most colors are not 100 percent saturated. Then any color diluted by white light has all three primaries.' Assume 70% saturation for yellow. Now this color has two components: 70% saturated yellow and 30% white.

70% Yellow produces	0.70R	0.70G	0.00B
30% White produces	0.30R	0.30G	0.30B

Total output is 1.00R 1.00G 0.30B

$$Y(\text{luminance}) = 0.30(1.00) + 0.59(1.00) + 0.11(0.30) = 0.923$$

We can see that this color is "brighter" than the saturated yellow which has a luminance value of 0.89. Note that the addition of white to desaturate a color increases the luminance value and decreases the chrominance value, compared with 100% saturation.

ANALYTICAL AND EXPERIMENTAL METHOD

The first step in the study of color machine vision is to extract the color information from a scene. Natural scenes in general consist of more than one color. Human beings use color information as a powerful clue in object recognition. Traditional binary machine vision has neglected the color component in the scene by thresholding the grey-scale image. This is an original study in extracting color information from a scene through filtering, yet still preserving the processing speed and other advantages of a "binary" vision system.

The study of colors involves usage of narrow- or broad-band filters installed in front of viewing TV cameras or broad-band light sources, or by directing manipulating the chrominance (and luminance) signals in a color TV camera. The choice of narrow or wide band filters depends on several factors. The number of colors to be discriminated, the distribution of these colors in the visible spectrum, and the amount of processing time involved determine how many filters to use and what bandwidths to use.

The commonly used color filters are color additive filters and color subtractive filters. Color additive filters used are broad bandpass and edge interference filters which transmit one of the three primary colors (red, green and blue). Combined in suitable mixtures, these colors can produce most of the color sensations which human vision is capable of perceiving. The color subtractive filters are designed for use at 45 degrees and reflect the primary colors red, green, and blue. The transmitted colors are the complementary colors of the primaries. These are cyan (minus red), magenta (minus green), and yellow (minus blue). Minus colors are often used electronically and photographically to reproduce the primary colors. For example, the strength of the red signal at a vidicon may be determined by obtaining the white light signal and subtracting from it the minus red (cyan) signal. In fact, a minus red channel, a minus blue channel, and a white light channel are sufficient to obtain the information to reproduce the primary colors, and is the basis of some inexpensive color television cameras.

Narrow-band color filters are chosen to select the bandpass of the field of view. Only light with the specified narrow bandwidth can be tramsmitted and thresholded. The advantage of this approach is that color can be more accurately acquired and differentiated. The shortcoming is that in order to process a large number of colors, a corresponding large number of narrow-band filters has to be utilized.

Discrete objects with distinct single color regions can be easily differentiated. Objects with several color patches can be analyzed in the following way. The individual patches are analyzed and features computed. The identified individual patches can later be "recombined" through utilization of features such as area, center of blob, pixel counts.

Selecting and Characterizing the Light Source

Color sensing results from the compound spectral effect of the color filters, the light source, and the imaging sensors. Manufacturers of filters usually provide the transmittance curves for precision filters. The spectral responsivity functions of the sensors and the spectral power characteristics of the light sources are also important parameters which must be measured or obtained from the suppliers of the instruments.

The human eyes in general do not discriminate composite colors very well. A source may appear white but has a far-from-flat spectrum. In order to select the appropriate light source, the authors have performed a detailed monochromator test of all existing light sources available in the laboratory. These sources include tungsten halogen lamps, fluorescent lamps, infrared and ultraviolet sources. The spectral characteristics of these sources are documented by obtaining the spectrographs for all sources. This procedure is important in selecting a light source which has relatively flat bandpass in the visible spectrum.

Decision was made to use the "north sky-light" fluorescent lamp as the light source to perform the experiment to be discussed. We chose fluorescent lamp for high luminance and most importantly, for more uniform spectral power distribution than other sources such as tungsten ones(See Figure 5.1.).

Characterizing the Color Filters

A similar experiment was performed to characterize the transmitting characteristics of the color filter sets. The filters tested included a set of color additive filters, a set of color subtractive filters, and a set of color-temperature compensation filters manufactured by Melles Griot Corporation. The first set consists of red, green and blue filters. In addition to the transmittance curves supplied by Melles Griot, the spectral property of these filters was actually tested by using a monochromator. The transmittance curves of these filters under illumination of the fluorescent lamp are shown in Figure 4.2 - 4.4. These curves clealy show how the filters cut off certain ranges of wave-lengths in the spectrum.

Rejection of Unwanted Colored Object using Color Filters

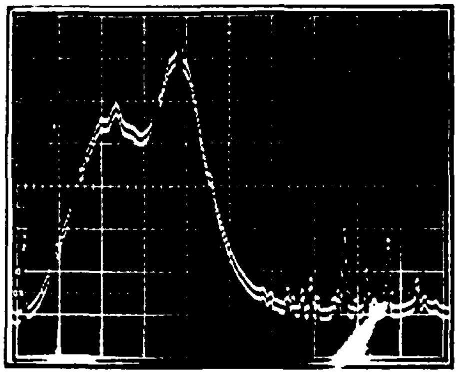
The methods of discriminating colors using current machine vision system fall into two categories: methods based on slection of spectral passband and methods based on luminance effects of color objects.

The are two problems involved in the latter process. The first concerns the optimal selection of single threshold for all colors. The second is the confusion caused by the fact that different colors may have the same luminance value. This makes any discrimination based on luminance alone unreliable unless during the training period the ambiguous situations are avoided.

An optimal solution to this is through the usage of a combination of the above two methods. Confusion caused by nonunique mapping between the color space and the luminance space can be minimized by using filters to eliminate undesired spectral contents. If a small number of filters is used(say, R, G, and B filters) to discriminate colors widely-spaced in the visible spectrum, then the filters alone will be sufficient to distinguish them using "binary" color vision. For colors with overlapped spectral contents, the luminance effect of colors will be useful in color-differentiation in combination with filters in "binary" vision system.

Luminance Effect of Colored Objects

An experimental testbed (See Figure 6., 7.) was established to experiment and evaluate machine color vision. This test-bed consisted of a MI VS-100 binary computer vision system, a color filter holder with adjustable supporting stand, the color-additive filter set, a set of plastic color rings with identical shape and size as test objects, and the optional MI DS-100 Machine Vision Development System[1](Chen and Milgram, 1982) for developing special software for color-coding and performing the training and recognition functions. An experiment was performed to assess the feasibility of discriminating multiple colors using single filter. A set of color rings were prepared as the testing objects. The set of rings used consists of red, pink, yellow, and blue. Placed under a TV camera connected to the MI VS-100 vision system, the blue ring was invisible (rejected) to the system under a red filter (In an automated factory, this feature allows automatic rejection of unwanted color objects in the background. This also saves computing time by neglecting the otherwise complicating objects in connectivity analysis). A comparison of the filtered and unfiltered view would identify the blue ring.



wavelengths(nm)

(starting at 350 nm, with 65nm spacing)

Figure 4.1. The spectral distribution curve of the fluorescent lamp used to perform the experiments described in this paper.

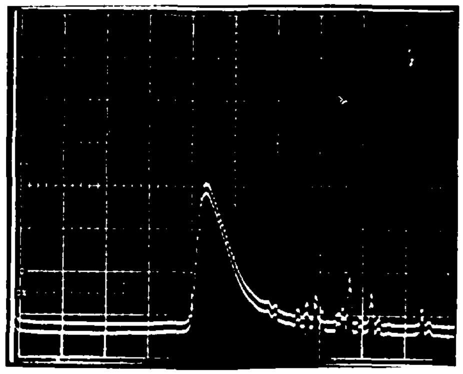


Figure 4.2. The transmittance curve for the red filter with the fluorescent lamp as the light source.

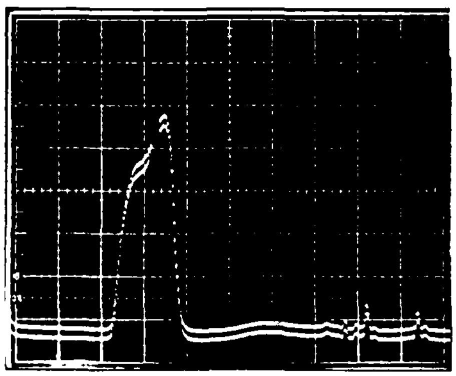


Figure 4.3. The transmittance curve for the green filter with the fluorescent lamp as the light source.

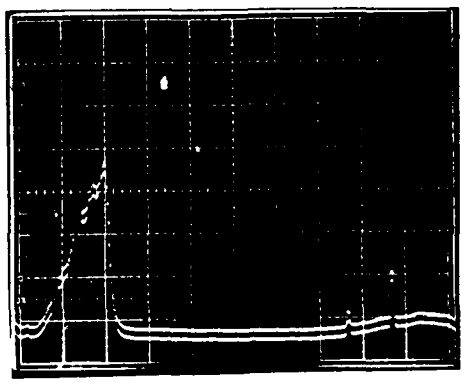


Figure 4.4. The transmittance curve for the blue filter with the fluorescent lamp as the light source.

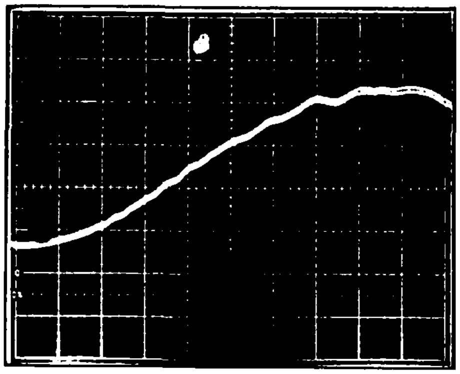


Figure 5.1. The spectral distribution curve of a tungsten lamp.

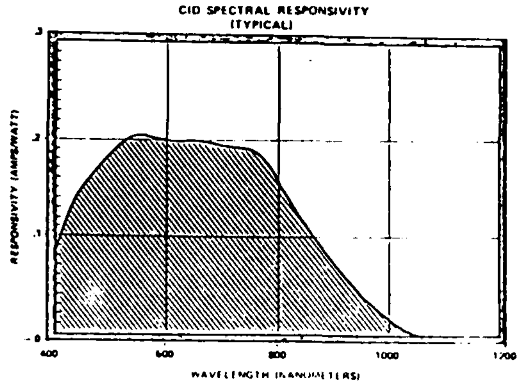


Figure 5.2. The typical spectral responsivity curve of the CID solid-state camera used in the experiments.

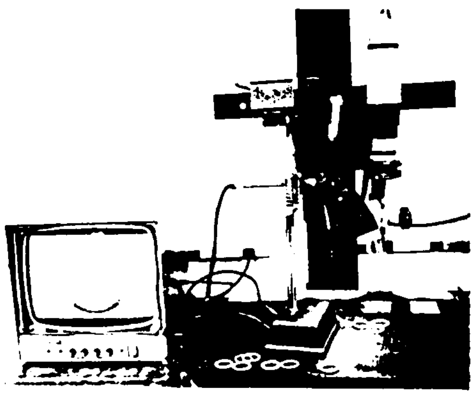


Figure 6. The experimental setup for color discrimination using binary processing.

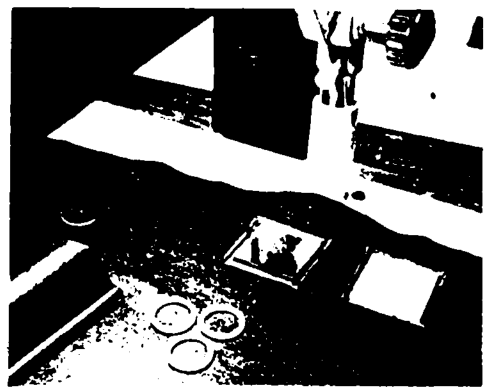


Figure 7. Close-up view of the color rings used in the experiments and the filters.

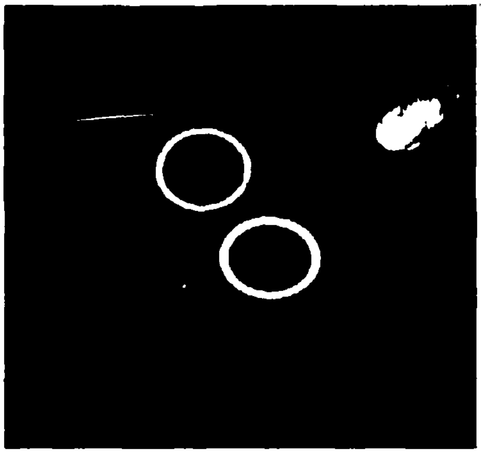


Figure 8.1. The raw video image of the red, green and blue rings with the finger pointing at the blue ring.

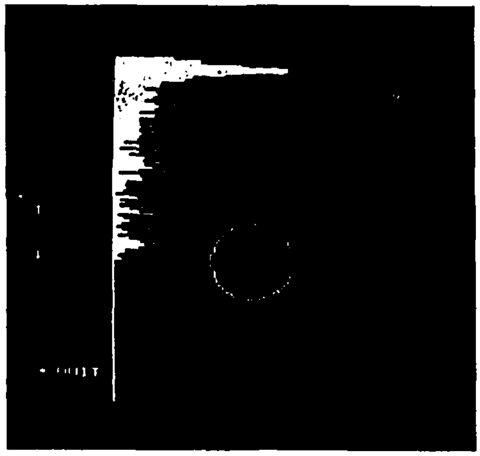


Figure 8.2. At a threshold value of 96, the green ring appears first because of its highest luminance.

Figure 8.3. At a threshold value of 49, both the green and red ring show their thresholded images.

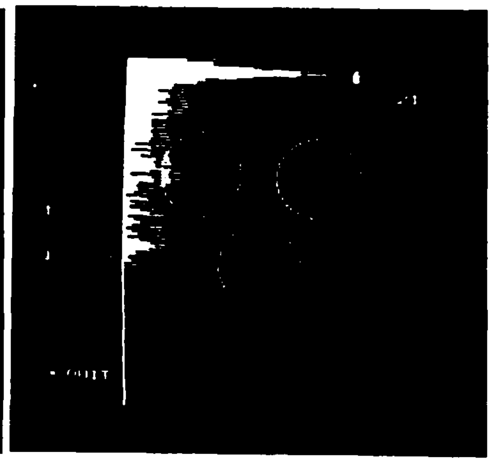


Figure 8.4. At a threshold value of 21, all three rings appear on the monitor. The blue ring seems to be thinner than the other two ring.

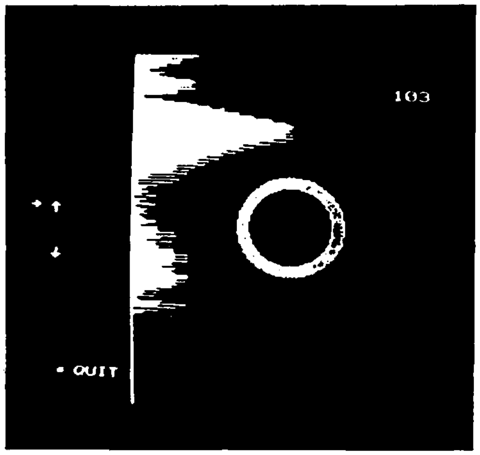


Figure 9.1. The histogram of the red ring without red filter.

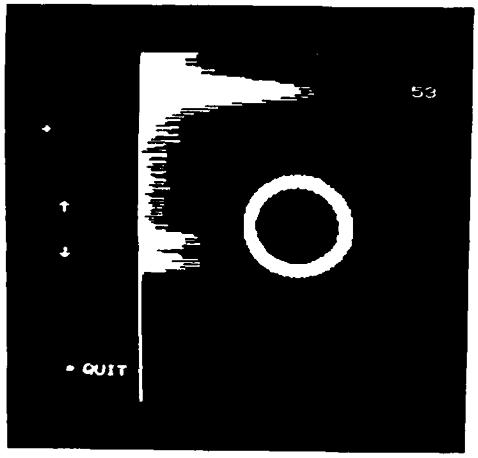


Figure 9.2. The histogram of the red ring with red filter.

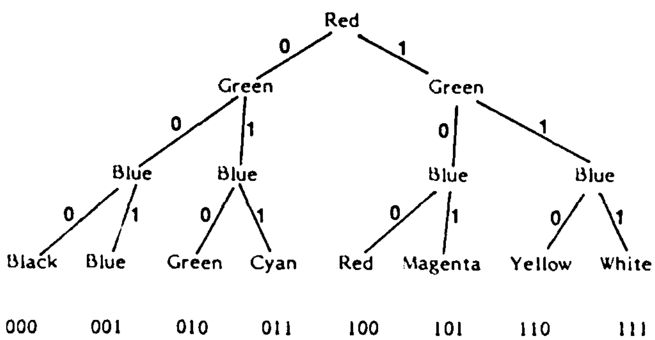


Figure 10. The classification and coding technique used in analyzing colors. A 3-bit code is associated with each classified color. A maximum of eight colors can be classified using this method.

As explained in the previous sections, luminance indicates the amount of light intensity, which is perceived by the eye as brightness. Different colors have different shades of luminance as some colors appear brighter than the others. Relative luminosity curves have been produced by color scientists to show the hue/luminance relationship. The relationship indicates that the green hues between cyan and orange have maximum brightness. The rings showed different total pixel-counts(or area) for different colors under the same thresholding value. This is a "feature" that the VS-100 binary vision system can utilize to perform discrimination task for parts with the same feature-set except differences in colors. The authors have successfully used this property to distinguish the colors described.

Figure 8.1.-8.4. show the histograms and the thresholded images for the red, green and blue rings at three different threshold settings. It is interesting to notice that the green ring appears first as the threshold sweeps from the bottom to the top in grey levels, followed by the red ring, and then by the blue ring. It was pointed out in the previous section that green appears brightest in comparison to the other undiluted colors. This phenomenon can also be easily observed in the raw video image that shows the three rings with a black background. The finger points at the blue ring which appears darkest.

Color-Coding Technique

Utilizing color filters for the three primary colors, color-encoding can be performed. Basically, this operation is, in principle, similar to the early design of color video cameras which used a rotating color-filter wheel triggered by the vertical sync signal for color separation.

We can use a 3-bit color-encoding technique to code and distinguish eight colors. Figure 10. shows the binary tree classification method used in color encoding and classification. We can see that 3-bit encoding works best for three primary and their complementary saturated colors. For desaturated colors, because of the dilution by white(in other words, mixture with equal amount of red, green, and blue primaries), ambiguity will arise. For example, light green, pink, and light blue may all be indistinguishable from white in coding since they are all coded 000. Another example is that yellow and orange may both have the same coding 110, i.e., both of them will pass the red and green filter test and fail the blue filter one, despite that they are different colors as perceived by the human eyes.

CONCLUSION

The unique aspect about this research is that color is acquired together with all other features in a "binary" machine vision system. Traditional color discrimination devices such as monochromators or spectrophotometers only analyze a beam of light instead of a scene viewed through a camera as perceived by the human eyes. By combining MI VS-100 machine vision system with color filters, color, as well as location, shape and orientation descriptors can be easily obtained. This combined color/location/orientation information can be used by a robot arm or other manipulators to pick up a distinguished colored object. Additionally, through usage of filters, irrelevant colors can be easily rejected. This is particularly important in saving computer processing time by filtering away cluttered background noise. Objects with connected multicolor regions can be recombined by using other features such as area, center, and pixel counts. Color codes can be identified on a complex background. The limitation posed by connectivity analysis can be easily removed. For example, a red object in contact with a blue one can be readily perceived as isolated ones through filtered views. The same scene will be easily misinterpreted by conventional binary vision system as single object because of the usage of blob processing and run-length encoding.

It is easy to imagine that the introduction of color differentiations for current machine vision processing will greatly extend the range of applications. This paper addresses some of the important issues of color filtering and binary processing as a foundation for our continual effort in this research.

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